GENESIS, CLASSIFICATION, AND LAND USE POTENTIAL OF SOME ULTISOLS OF MAUI, HAWAII

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I. INTRODUCTION

The Island of Maui is the second largest island in the State of Hawaii, with an area of 1,887 square kilometers or 728.8 square miles (Armstrong, 1983). It is located in the tropics at latitude 20°34'30" to 21°02'05" North and longitude 155°58'50" to 156°42'30" West. The most prominent geological features of the island are the two volcanic mountains of Mount Haleakala on the east and the West Maui Mountain on the west, separated by the great central valley called the Isthmus.

West Maui is a deeply dissected volcano rising to 1,764 meters (5,788 feet) at Puu Kukui. The central portion of West Maui consists of canyons and steep ridges. Surrounding the central portion is a narrow belt of moderately sloping land covered by pineapple and sugarcane. The central Maui Isthmus connects West and East Maui. The land is smooth and nearly level and is used extensively for sugarcane. East Maui is dominated by Haleakala, a 3,055-meter (10,023-feet) dormant volcano. Near the summit and on the eastern and southwestern slopes, the land is rough and rocky. The western and northern slopes are relatively smooth but are sloping to moderately steep.

Maui island is within the belt of the northeast trade winds. Excessive precipitation occurs on the windward sections of the mountain and is relatively light over the leeward sections. The height of Haleakala is sufficient to divert the trade wind flow laterally around it rather than allowing the air to flow over the top. Yet sufficient vertical lifting occurs to provide an orographic annual rainfall of over 10,000 mm (400 inches) at the wettest place. The rainfall decreases in the higher elevation and westward portions. In some areas with different elevations, the annuals rainfall is somewhat the same.

The belt of maximum rainfall on East Maui is at 900 meters (3,000 feet), decreasing toward both higher and lower elevations (Leopold, 1949).

In relatively restricted areas, soils derived from similar parent materials of nearly identical geological age, vary in the degree of weathering and development. Different soils are found within a short distance of each other due to large variations in climate, and, to a certain extent, because of the volcanic ash parent material. On the other hand, similar soils are found at different elevations because of similarity in rainfall. Soil formation, therefore, is essentially a study of climosequence and, to a certain extent, geosequence.

The study of Ultisols is of special interest because they are the infertile soils of the tropics which, with proper management, have potential for certain kinds of uses. Because limited information is available in developing the classification of these kinds of soils in the tropics (Soil Survey Staff, 1975; Moormann, 1979) they have also been the subject of much study recently by the International Committee on the Classification of Soils with Low Activity Clays (ICOMLAC).

The aim of this research, therefore, is to provide more information in classifying the Ultisols according to the proposal of the ICOMLAC (SCS, 1984a). Because the properties of soils are influenced by soil forming factors, the dominant role of climate and parent material will also be associated.

The objectives of this thesis research, therefore, are:

(1) to study the influence of climate and parent material on the

formation of some Ultisols in the northern part of East Maui, (2) to verify the classification of these soils according to Soil Taxonomy and to test the proposal of the International Committee on the Classification of Soils with Low Activity Clays (ICOMLAC), and (3) to determine the land use potential of these soils.

II. REVIEW OF LITERATURE

2.1 Geology of Maui

The island of Maui is formed largely from lava flows, both pahoehoe and aa, erupted from two volcanoes that built Haleakala on East Maui and the West Maui Mountain. The flat isthmus connecting the two volcanoes was formed by lavas from Haleakala banking against the West Maui Mountains and sedimentary materials (Medearis, 1975).

Stearns (1966) explained that the West Maui Mountains are incised by deep amphitheater-headed valleys and are overlapped by lava flows on the east from Haleakala which have built a saddle known as the Isthmus. Iao valley is an old caldera tapped by the Wailuku river and enlarged by erosion. Although rift zones are known, this volcano approaches the central type, in contrast to the fissure type, because dikes radiate in all direction from the ancient caldera and almost all of the lava beds are steep and many of them are poured from the central vent. Single basaltic dikes as much as seven meters across, the widest basaltic dikes yet found in the island, crop out on West Maui.

On East Maui, the volcano is built over three rift zones and is studded with large cinder cones. In many places, three series of lava can be distinguished. The lower unit, the Honomanu volcanic series, consists of thin-bedded typical basaltic pahoehoe and aa. Overlaying this unit conformably is the Kula volcanic series, composed chiefly of thicker andesitic aa flows which issued in a more viscous state and which contain many interstratified thin ash-soil layers. Because many of the large cinder cones were built during the Kula epoch, ash beds are more numerous than in lower underlaying Honomanu basalts. Some olivine basalt and picrite basalt occur in the Kula series. The third and upper unit is the Hana volcanic series, consisting of ultrabasic olivine augite porphyries to nonporphyritic andesites.

Hinds (1925) stated that the principal volcanic center on Haleakala probably became extinct in the late Pleistocene, although the eruption of the cinder cones and lava flows in the summit depression evidently took place much later, because they are definitely younger than the lava of the surrounding scarps. Subsidiary activity continued as late as 1750, when small flows from fissures not far from the sea on the southwestern side buried part of a Hawaiian village. The volcano last erupted about 1970 (Stearns, 1966).

Stearns (1966) stated that "a long quiescent period followed during which canyons were carved in the volcano, although a few eruptions may have occurred during this erosion interval. After this rest period, copious flows once more issued but along the southwest and east rifts only. These lavas partly filled the canyons and veneered most of the mountains except tracts adjacent to the northwest rift."

Macdonald et al. (1983) described that the primitive shield of Haleakala volcano is composed of pahoehoe and aa flows of tholeiite, tholeiitic basalt, and oceanite averaging about five meters in thickness, with which are associated very minor amounts of pyroclastic materials. The assemblage is known as the Honomanu volcanic series. Above sea level the shield has been almost wholly buried by later lavas. It is now exposed only in sea cliffs along part of the north shore, in the walls of Honomanu and Kaenae valley, along a short stretch of the north wall of Kipahulu valley on the eastern slopes, near the head of the deep

Manawainui Canyon on the southern slope, and possibly in the lower part of the south wall of the Haleakala crater.

The Honomanu series is overlain by the Kula volcanic series composed predominantly of hawaiite with lesser amounts of alkalic olivine basalt and ankarmite.

The Kula eruption took place from three well-defined rift zones. Most prominent are those extending southwestward and east-northeastward from the summit, forming a nearly straight line across the mountain. The third rift zone, extending north-northwestward from the summit, is much less prominent but is clearly marked by the rows of cinder cones that extend almost to the coast. Many large cones of the Kula series lie along the upper part of the southwest rift zone.

The Kula flows are well-exposed in the cross section in the walls of Haleakala crater and in Keanae and Kaupo valleys and they form the surface over most of the northwestern segments of the mountain. Eruptions were more explosive than those of earlier series, and many large cinder cones were formed. Beds of poorly consolidated vitric ash are common, and they are as much as nine meters thick. The flows are characteristically thicker than those of the Honomanu series. Aa, commonly with a tendency toward block lava, is predominant but some pahoehoe is present near the vents. Few small domes are exposed in the cross section in the wall of the crater. Near the summit of the mountain, the Kula series is at least 750 meters thick but near the shore it is only 15 to 60 meters thick, at many places consisting only of the single flow. Occasional lenticular beds of hillwash debris and stream-deposited gravel occupying shallow gulches are found between lavas of the

Kula series, indicating that, at least locally, some moderately long intervals occurred between eruptions.

Toward the end of the Kula period, the interval between eruptions increased, and local erosional unconformities, soil beds, partly weathered beds of ash, and stream-deposited conglomerates were commonly found between the flows. Some of the canyons cut in the Kula lavas and filled by later Kula flows are a few hundred meters deep and must indicate time intervals of hundreds, if not thousands of years.

The lava flows and associated cinder cones and ash deposits that erupted after a long period of erosion are called the Hana volcanic series. The rock types are the same as those in the Kula series, but alkalic olivine basalts and basaltic hawaiites are predominant over the more siliceous types. One of the outstanding characteristics of the Hana lavas is a marked deficiency in silica. In general, the Hana lavas erupted in a more fluid condition than the Kula lavas, and the flows tended to be thinner and less massive.

Still later, Hana lavas again flooded the valleys and partly filled the canyons. Hana lavas are absent on the entire northwestern sector of the mountain, because the north rift zone of the Kula series did not reopen.

According to Macdonald et al. (1983), the study area is dominated by the Kula lavas, and some Honomanu lavas are also found in the sea cliffs along part of the north shore. The Kula volcanic series have dominated the northern part of East Maui, where the soil samples have been collected

2.2 Climate

According to Hinds (1931), the Hawaiian Islands are within the belt of the northeast trades with winds blowing over the surfaces with more or less constant velocity. Depending upon the elevation, there are moderate to extreme differences of temperature from sea level to the mountain summit, usually with extraordinary variation in the annual rainfall within a limited distance over the same mountain. There are many climatic contrasts, therefore, in areas that are only a few kilometers apart.

The rainfall, which is the most variable of the climatic elements, is heaviest over the windward slopes and relatively light over the leeward portion of the various domes. The leeward slopes of the higher domes furthermore receive lesser amounts of rainfall as sea level is approached, and the climates vary from tropical highland isothermal at the highest elevations to savanna at the intermediate levels and distinct aridic areas near sea level. Precipitation and temperature, therefore, are major climatic factors affecting soil formation in Hawaii.

In Hawaii, the rainfall ranges from less than 250 to 11,580 mm (10 to 456 inches) on a mean annual basis and is determined by exposure to the prevailing wind, elevation, and local topography (Britten, 1962).

On East Maui, the precipitation is less over the southwestern slopes than over the northern and northeastern slopes. Rainfall ranges from 250 mm in the desert of Mt. Haleakala's rainshadow to 3000 mm in the rain forest exposed to the northeast trade winds. The mean annual temperature ranges from 25° C at sea level to 13° C at 1800 meters above sea level. According to Leopold (1949), the belt of maximum rainfall on East Maui is at 900 meters (3000 feet); the rainfall decreasing at higher and lower elevations. The forest ends abruptly at approximately 2100 meters (7000 feet) and is replaced by xerophytic zones of shrubs and grasses at higher elevations.

Figure 1 shows the median annual rainfall distribution on Maui (Department of Land & Natural Resources, 1982), while Tables 1 through 3 (Leopold, 1949; Taliaferro, 1959; Hawaii State Dept. of Land & Natural Resources, 1982) show rainfall data collected at some of the gages located in the area where soil characteristic samples were obtained for this study.

Depending almost entirely on elevation, the temperature varies little from summer to winter. It is, however, affected in a minor way by the slope and exposure to the wind.

Britten (1962) stated that "the location within Tropical Zone plus the insular condition give the islands temperatures which at sea level are warm throughout the year. Excessively high temperatures are not encountered because of the maritime conditions."

Britten (1962) further found that in Maui, there was a decrease of approximately 1.7° C (3° F) for each 300 meter (1000 feet) increase in elevation. Sanchez (1976) on the other hand, mentioned that in general there was a decrease of 1.98° C (3.56° F) for every 300 meter (1000 feet) increase in elevation in the tropics.

2.3. Genesis and Classification of Ultisols

Ultisols are mineral soils of mid to low latitude or intertropical region and humid climatic region. The most intimate factors in the formation of Ultisols are climatic factors such as rainfall and temperature.

According to Soil Taxonomy (Soil Survey Staff, 1975) the Ultisols

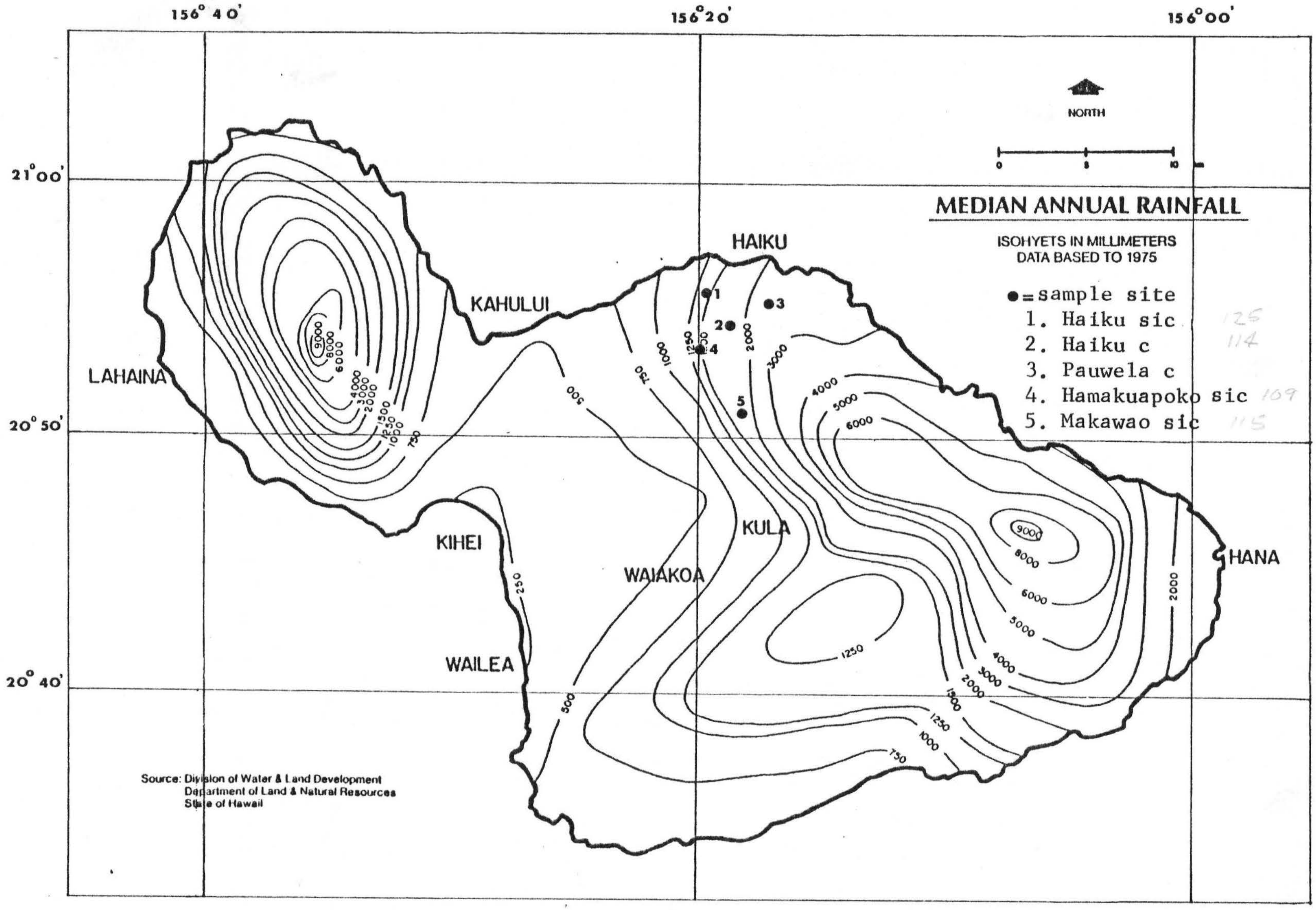

Figure 1. Median annual rainfall isohyets of Maui

Table 1. Mean and adjusted mean annual rainfall in mm near the pit sites.

Pit sites	No.	Station	Elev. (m)	Period of record	Mean	Adjusted mean
NifTAL Pauwela site	485	Hamakuapoko	95	1907-39; 42-48	1280	1275
	486	Field 202	91	1939-48	1014	1092
	488	Kaiku (A&F)	137	1937-38; 40-44 1946	1951	1981
NifTAL Kuiaha site	421	Field 206	213	1948	1415	1181
		Haiku	252	1925-38	1664	1669
	490	Haiku (Libby)	143	1925-48	1636	1707
Pineapple Haliimaile site	423	Haliimaile	326	1934-48	1057	1092
	430	Fiel 210	335	1934-48	1260	1303
		Grove Ranch Office	372	1925-31	1364	1382
Haleakala Exp. Station site	433	Piiholo	579	1928-48	1826	1880
	434	Haleakala Branch sta.	658	1922-48	1961	2017

Source: Leopold (1949).

Table 2. Annual rainfall recorded from the gages near the pit sites.

Pit sites	Gage No.	Elev.(m)	Period of record	Rainfall in mm		
				Max.	Med.	Min.
NifTAL Pauwela site	485	95	1884-1958	2075	1232	521
	488	137	1939-1953	2558	1882	953
NifTAL Kuiaha site	490.1	139	1925-1940	2121	1689	1219
	490	148	1916-1958	2604	1702	926
Pineapple Haliimaile site	430	335	1934-1957	2030	1313	589
	425.1	372	1924-1931	1844	1339	622
Haleakala Exp. Sta. site	434	579	1921-1957	2858	1880	813
	434.1	659	1938-1957	2352	1466	602

Source; Taliaferro (1959).

Table 3. Median annual rainfall and the averages of rainfall for each month of some gages near the pit sites, in mm.

Gage No.	Record years	Annual median	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.
NifTAL Pauwela site														
485	78	1265	117	99	125	112	71	53	76	79	51	76	112	119
488	15	1864	140	119	180	158	137	86	117	112	71	125	117	170
NifTAL Kuiaha site														
486.2	21	1915	107	130	183	185	119	91	117	127	91	127	180	183
490	54	1727	168	117	147	150	117	91	117	117	86	107	142	170
Pineapple Haliimaile site														
430	39	1318	137	124	135	107	74	33	69	66	33	69	99	142
485.2	14	777	112	79	58	74	48	38	46	38	28	43	56	97
Haleakala Exp. Station site														
434	54	1829	185	188	201	170	86	53	71	79	43	97	155	185
434.1	26	1400	127	137	203	130	58	20	46	51	20	89	97	142
Ulumalu area														
488.3	15	2499	211	167	185	262	183	130	226	165	142	140	244	168
491	14	2057	188	142	152	183	158	109	122	145	86	122	165	218

Source: State of Hawaii, Dept. of Land and Natural Res. Division of Water & Land Development (1982).

are confined to the areas where the soil temperature regime is mesic, isomesic, or warmer. They have an argillic horizon and base saturation of less than 35% (by sum of cations) at 1.25 meters below the upper boundary of the argillic horizon or 1.8 meters below the soil surface or at a lithic or paralithic contact whichever is shallower. Plinthite and fragipan are also found in subsoil of some Ultisols, particularly in areas with repeated wetting and drying.

2.3.1. Genesis of Ultisols

Two overlapping steps are associated with soil genesis, namely, the accumulation of parent materials and the differentiation of horizons in the soil profile (Simonson, 1959). The four important processes in horizon differentiation are (1) additions, (2) removals, (3) transfers, and (4) transformation. Examples include the accumulation or addition of organic matter or carbonate, removal of soluble salts, and the transfer or transformation of silicate clay minerals. In almost all soils, these processes operate not only individually but also in combination with others. Previously, the soil forming processes were associated with a particular kind of soil; for example, podsolization for Podsols and laterization for Latosols.

According to Sherman (1949), the two weathering processes associated with the genesis of tropical soils are (1) transformation of primary minerals to kaolin clay minerals and (2) the decomposition of these clay minerals and the accumulation of the free oxides of Fe, Al, and Ti. Kaolin, gibbsite, and other sesquioxides and oxyhydroxides are generally regarded as the colloidal end products of weathering in the tropics. (De Villiers, 1965).

One of the diagnostic properties of Ultisols is the presence of an argillic horizon, a subsurface horizon with an illuvial accumulation of layer-lattice clays and usually as cutans or clay films. This horizon is formed by precipitation in which the lessivage process occurred. According to Buol et al. (1980), lessivage is a mechanical migration of small particles from the A horizon to the B horizon in a soil profile, with a subsequent relative enrichment of clay in the B horizon.

Steila (1976) mentioned that certain conditions were required in the formation of the argillic horizon: There must be the presence of very fine clays, either from the parent material or from weathering, and there must be a dispersion of the very fine clays. If mineral salts such as carbonates and free oxides were present, it was necessary that these constituents were weathered chemically and removed prior to the clay migration.

Several conditions were also specified by Eswaran (1979). It was necessary that the clays were capable of movement. If clay platelets were cemented by sesquioxides, they were dispersed prior to movement. The optimal soil acidity was pH 4.5 to 6.5 and the moisture status was one in which there was alternating wet and dry conditions. The ideal conditions for the formation of cutans or clay skins was when the subsoil was dry or partly dry.

These cutans are described (Soil Survey Staff, 1975; Steila, 1976) as being translocated clays forming coatings of oriented clay particles on channels through which water moved or collected. The channels, furthermore, are decribed as being principally bounded by ped cleavage faces or pores associated with roots or animals.

The lessivage process is not recognized by all. Simonson (1949) suggested that there can be formation of silicate clay minerals in subsurface horizons of soil classified as Ultisols. This idea is supported by Isbell (1980) who concluded that concurrent formation of clay should not be precluded in illuviation and that most of the clay in the argilllic horizon either formed in place or was inherited from the parent material.

Although cutans are common features in many of the Ultisols, it is not easily recognized in some soils, especially those in which the subsurface horizon is dominated by kaolin minerals (Soil Survey Staff, 1975; Buol et al., 1980). The clay increase in illuvial horizon in relation to the eluvial horizon, however, is an important criterion in recognizing the argillic horizon.

In addition to the clay increase in argillic horizon, a low base saturation, less than 35 percent by sum of cations method, is another important property of the Ultisols. Low base saturation, together with acidic reaction, in or immediately below the argillic horizon is due to extensive leaching in Ultisols. The combination of extensive leaching and high soil temperature over a long period of time, furthermore, have resulted in the rapid and complete alteration of weatherable minerals into secondary clay minerals or oxides. They include not only kaolinite, gibbsite, and chlorite-vermiculite intergrades (Buol et al., 1980; Foth and Schafer, 1980) but also the various oxides of Fe and non-crystalline materials of Si, Al, Fe, and Mn (Jones, 1983).

2.3.2. Classification of Ultisols

Ultisols were previously classified as Latosols, Red-Yellow Podzolic soils, or Reddish Brown Lateritic soils (Sherman et al. 1948; McCaleb, 1959; Buringh, 1970; Buol, et al. 1980; Tan and Perkins, 1980; and Foth and Schafer, 1980). According to Cline (1955), the Ultisols in Hawaii are generally those classified as Humic Ferruginous Latosols and Humic Latosols. The Haiku and Pauwela soil series were Humic Ferruginous Latosols, while the Makawao soil series was a Humic Latosol. The Hamakuapoko soil series, on the other hand, was a Low Humic Latosol (Cline, 1955; Foote et al., 1972).

According to Soil Taxonomy (Soil Survey Staff, 1975), the order of Ultisols is subdivided into five suborders, they are, the Aquults, Humults, Udults, Ustults, and Xerults, based on soil moisture regime and/or organic matter content. The Aquults (aquic moisture regime) are wet Ultisols with a fluctuating water table and usually have low chroma below the Ap or Apl horizon. Humults, on the other hand, are those with high organic C content and are more or less freely-drained. The Udults (udic moisture regime) are also relatively freely-drained soils of the humid region but with low organic C content and generally have a light-colored epipedon over yellowish-brown to reddish argillic horizon. The Ustults (ustic moisture regime) are relatively freely-drained soils with low organic C content and most have reddish color. Finally, Xerults (xeric moisture regime) are found in areas of dry summer and moist winter.

All of the Ultisols of Hawaii are classified in the suborder Humults and in the great group Tropohumults. Because of the low cation exchange capacity, they are, furthermore, classified as Orthoxic or Humoxic subgroups (Foote et al., 1972). In Hawaii, these Tropohumults occur on gentle slopes of terraces, alluvial fans, and foot slopes. On the northern part of East Maui, they occur on the foot slopes of the Kula volcanic formation (Foote et al., 1972).

In 1975, the International Committee on Classification of Soils of Low Activity Clays (ICOMLAC) was organized under the leadership of Dr. Frank R. Moormann of the Netherlands, in order to recommend changes in the classification of Ultisols and Allfisols with low activity clays. In the ICOMLAC's proposal, an additional diagnostic subsurface horizon, a kandic horizon, was proposed based primarily on clay content increase with depth and not on the presence of clay skins or bridges of clay films between sandgrains. In summary, the kandic horizon is a subsurface B horizon with significantly higher percentage of clay than the surface horizon, and it has a cation exchange capacity (CEC) of less than 16 meq/100 g clay or an effective cation exchange capacity (ECEC) of less than 12 meq/100 g clay in the major part of the horizon.

New great groups of Ultisols and Alfisols have been introduced, and some of the existing great groups of Ultisols and Alfisols have been deleted, for example, the "trop" great groups, Umbraquults, and Palehumults (SCS, 1984a).

2.4. Use of Ultisols and Potentials of Leucaena and Eucalyptus

Ultisols are relatively infertile soils because of their low base saturation and acidic reaction. These soils, however, have potential for crop production under proper management when they have an abundance of rainfall and a long growing season. As stated by Foth and Schafer (1980), Ultisols are generally well supplied with water for agriculture but are deficient in plant nutrients.

On Maui, the major agricultural crops are sugarcane, pineapples, and vegetables. Most of the areas mapped as Haiku clay are used for pasture and homesites, while those mapped as Haiku silty clay are in pineapples and homesites. The Hamakuapoko series is used for pineapples, while the Makawao series is in pineapples, vegetables, pasture and homesites. The Pauwela series is generally used for pasture with small areas in pineapples.

Although there are certain limitations, leucaena and eucalyptus are observed growing on these soils. One of the limitations of leucaena is soil acidity, while that of eucalyptus is poor drainage (Cagauan et al., 1982).

Both leucaena and eucalyptus are cited for use as timber and fuelwood. In addition, leucaena has been used for reforesting eroded hill-slopes or for forage and manure (Ruskin, 1977). On the other hand, eucalyptus has been associated with fencing, protection of irrigation channel, windbreaks, shade trees, essential oils, pulp, fiber board, and minor uses (Zacharin, 1978). In Australia, the Eucalyptus globulus is one of the best commercial timber products.

According to Brewbaker (1980) the Hawaiian giant leucaena (Leucaena leucocephala) is adapted to tropical and subtropical climate in well-drained soils having a pH of 5.5 to 8.5. The preferred elevation for leucaena is below 760 m with an optimal mean annual rainfall of 760 to 1650 mm and an optimum temperature ranging from 18°to 32° C.

III. MATERIALS AND METHODS

3.1. Description of Study Area

The northern area of East Maui was selected for this study. According to the Department of Land and Natural Resources, (1982), the median annual rainfall increases from west to east with the mean annual temperature (MAT) held more or less constant, while the MAT decreases with an increase in elevation from north to south with the median annual rainfall held more or less constant (Fig. 1).

According to Foote et al. (1972), the dominant soils of the area are Ultisols and this soil order is represented by the Haiku, Pauwela, Hamakaupoko, and Makawao series. Table 4 shows the present classification of these soils according to Soil Taxonomy.

Table 4. Classification of Ultisols of Northern Area of East Maui (Soil Survey Staff, 1981)

Soil series	Soil family classification
Haiku	Humoxic Tropohumults, clayey, ferritic, isohyperthermic
Pauwela	Humoxic Tropohumults, clayey, oxidic isohyperthermic
Hamakuapoko	Orthoxic Tropohumults, clayey, oxidic isohyperthermic
Makawao	Humoxic Tropohumults, clayey, oxidic isothermic

Except for the Pauwela series, the soils that are listed in Table 4 were sampled in cooperation with the Soil Conservation Service, USDA. The soil profiles were described and collected using the procedure prescribed in the Soil Survey Manual (Soil Survey Staff, 1951). The location and general genetic factors of these soils are listed in Table 5, while the soil descriptions (Appendix A) are tabulated in Table 7, 9, 11, 13, and 15 in the section on results and discussions. Information relating to the Pauwela series was obtained from published data in the Soil Survey Investigation Report (SSIR) No. 29 (SCS, 1976).

3.2. Methods

3.2.1. Field sampling

The soil samples were collected in plastic bags and brought back to the laboratory for characterization according to procedure described in SSIR No. 1 (SCS, 1982). Before analysis, the samples were air-dried and ground to pass a 2-mm sieve.

3.2.2. Physical characterization

Particle size distribution of the fine earth fraction (particles less than 2 mm) was determined by the pipette method using Na hexameta-phosphate as the dispersing agent. Because many tropical soils form stable aggregates and disperse incompletely, for example, when oven-dried, the pipette method was modified as follows: After destruction of the organic matter with hydrogen peroxide, the sample was not oven-dried prior to the addition of the dispersing agent. A duplicate sample, however, was oven-dried to determine the oven-dry sample weight.

Water retention values were obtained at 33-kPa (1/3-bar) and 1500-kPa (15-bar) tension. Saran-coated clod samples were placed on 100-kPa (1-bar) pressure plate cells and a 500-kPa (5-bar) pressure plate extractor was used to obtain the 33-kPa values. Two-mm samples were used with the 1500-kPa (15-bar) ceramic plate cells and the 1500-kPa (15-bar)

Table 5. Locations and some genetic factors of the soils.

	Haiku sic (S84HA4-1)	Haiku c (S84HA4-3)	Pauwela c (S62HA4-4)	Hamakuapoko sic (S84HA4-4)	Makawao sic (S83HA4-12)
Location: Latitude	20°55'30" N	20°54'11" N	20°55'04" N	20°53'07" N	20°50'40" N
Longitude	156°19'37" W	156°18'24" W	156°17'18" W	156°19'46" W	156°17'51" W
Elevation (m)	137	283	192	350	640
Median annual rainfall (mm)	1450	1900	2500	1300	1800
Mean annual temperature (°C)	22	22	22	22	20
Vegetation, land use	pineapple	pasture	pasture, pineapple	pineapple	vegetable, pineapple
Parent rock	basic igneous rock	basic igneous rock	basic igneous rock	basic igneous rock	basic igneous rock
Topography, slope	moderately sloping	nearly level	rolling slopes	strongly sloping	gently to moderately sloping
	7%	2%		11%	5%
Soil drainage	well	well	well	well	well
Ground water	deep	deep	deep	deep	deep
Erosion	none	none	none	none	none

sic = silty clay, c = clay.

ceramic plate extractor to obtain the 1500-kPa values.

Bulk density was measured by the clod method and at 33-kPa tension. The clods were coated with Saran (1:5) prepared with methyl ethyl ketone.

3.2.3. Chemical characterization

Cation exchange capacity (CEC) was determined by two methods: The ammonium acetate extraction (pH 7.0) and the sum of cations methods. Extractable bases (Ca, Mg, Na, K) were analyzed in the ammonium acetate extract by means of the atomic absorption apparatus, while extractable acidity was determined in barium chloride-triethanolamine solution and back-titrated with hydrochloric acid. Base saturation was calculated by dividing the sum of the extractable bases by the CEC value determined by the ammonium acetate method.

Total organic C was obtained after the acid dichromate digestion, while total N was determined by the semi-micro Kjeldahl method. Extractable Fe was extracted with dithionate-citrate extraction, and extractable Al was obtained with 1N KCl extraction. Phosphate retention was the New Zealand procedure of using the nitric vanadomolydate acid reagent.

Soil pH was determined in water and in 1N KCl solution (1:1) as well as in 1N NaF solution.

The physical and chemical properties of soils are summarized in Tables 8, 10, 12, 14, and 16 in the section on results and discussions.

3.2.4. Land use potentials

In land evaluation, the suitability of a land for a specified purpose is determined by matching the land use requirements with the land qualities or land characteristics (FAO, 1976; 1984). Land characteristics include not only soil characteristics, such as chemical and physical properties, but also map unit or land-related features such as soil slope.

The potential of the soils of the study area was determined by matching the tree environmental requirements with the appropriate properties of Haiku, Pauwela, Hamakuapoko, and Makawao soil series. The environmental requirements of leucaena and eucalyptus are as follows:

Leucaena leucocephala is a species best adapted to the tropical lowlands with warm temperature and with mean annual rainfall ranging from 600 to 1700 mm. Leucaena grows well in neutral or alkaline soils where there is adequate amounts of exchangeable Ca (at least 2 cmol $(p^{+})kg^{-1}$) with little or no extractable Al (less than 60 percent Al saturation). Where there is no exchangeable Ca and Al saturation data, the soil pH (1:1 soil-water suspension) should be above 5.0.

Eucalyptus grandis is a species growing on bottomlands in Australia but adapted to tropical and temperate highlands with cool temperature and with mean annual rainfall ranging from 1000 to 1800 mm. The soil should be moist and well-drained.

Eucalyptus globulus is also associated with the temperate climate but it is better adapted to the higher elevation than E. grandis, with the mean annual rainfall ranging from 800 to over 1500 mm, well-distributed throughout the year. Limiting soil factors are shallow depth, poor drainage, and salinity (Ruskin, 1980).

IV. RESULTS AND DISCUSSION OF RESULTS

4.1. Morphological Properties (Table 7, 9, 11, 13 and 15)

At the lower elevations, going from west to east, the Haiku silty clay, Haiku clay, and Pauwela clay occur at 137, 283, and 195 m, respectively. In this transect, where the median annual rainfall ranges from 1450 to 2500 mmm, the soil color hue of the surface soil change from 7.5YR to 2.5Y. The apparent texture of the surface soil also changes from silty clay to clay and the wet consistence goes from very sticky and very plastic to sticky and plastic.

The change in texture can be associated with the transformation of primary minerals to secondary clay minerals (Sherman, 1949), while the changes in soil color and consistence can be due to accumulation of the free oxides of Fe, Al, and Ti during the weathering process (Sherman 1949; De Villiers, 1965).

At the higher elevations, again going from west to east, the Hamakuapoko silty clay and the Makawao silty clay occur at 350 and 640 m, where the median annual rainfall is 1300 and 1800 mm, respectively. Although the hue of the surface soil changes from 7.5YR to 5YR, the apparent texture and the wet consistence are essentially the same for both soils; that is, silty clay texture and very sticky, very plastic consistence, except for the Bw horizon of the Makawao soil which was just sticky and plastic.

4.2. Physical Properties (Tables 8, 10, 12, 14, and 16)

4.2.1. Particle size distribution

Figure 2 shows the clay distribution as obtained by the pipette method for all soils except the Pauwela, where the distribution is based

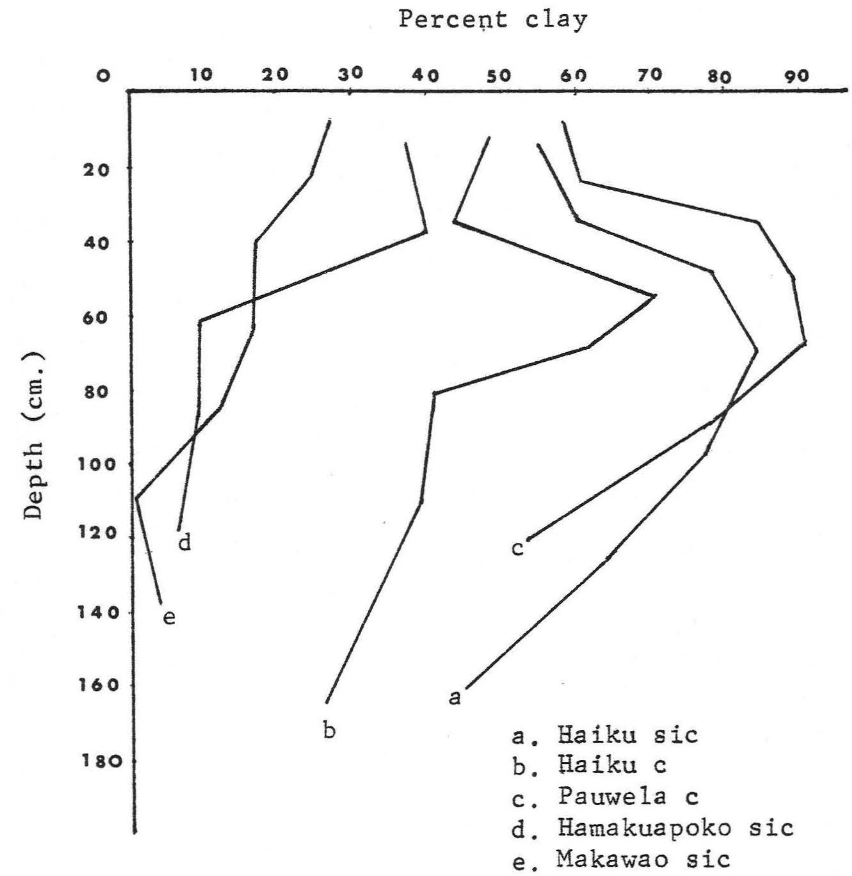

Figure 2. Percentages of clay as functions of depth

on 1500-kPa values because no particle size data were available for this soil.

Determination of particle size presents a problem in many tropical soils because of incomplete dispersion or because of stable aggregate information. Incomplete dispersion gives not only a low clay content (Ahn, 1979; Hillel, 1980) but also sometimes a high silt content (Lal, 1980). Associated with the stable aggregates are Fe and Al oxides which are capable of providing effective bonding between clay particles as long as these oxides occur in finely divided non-crystalline form (El-Swaify and Emerson, 1975; Lal, 1979; Hillel, 1980).

Table 6 shows the comparison of texture as obtained by the pipette method in the laboratory and as apparent texture in the field. The apparent texture is usually less clayey because of aggregated clay particles. However, this table shows that such is not the case for the Hamakuapoko and Makawao soils. The results suggest that these soils were not completely dispersed during the laboratory analysis. A high ratio ($>$ 0.6) of 1500-kPa water content to clay content indicates incomplete dispersion in these two soils.

Thus, for the determination of the clay content of the five soils, the clay content was estimated by multiplying the 1500-kPa water content value by a factor of 2.5. The original clay values, however, were used for the Haiku soils because the ratio of 1500-kPa water to clay was less than 0.6 in most of the control section. The percentage of clay or the percentage of 2.5 times 1500-kPa, whichever is greater, is used, provided the ratio of 1500-kPa water to clay is 0.6 or more in half or more of the control section (Soil Survey Staff, 1975).

Table 6. Particle size distribution and texture classes.

Soil	Depth	Horizon	Clay	Silt	Sand	Texture classes*		Estimated
						Pipet meth.	Field	clay cont.
	10^{-2}m		-------%--------					**
Haiku	0-28	Ap1	55.1	41.2	3.5	sic	sic	52
silty	28-43	AB	60.4	38.1	1.5	c	sic	56
clay	43-56	Bw	78.5	20.7	0.8	c	sic	66
	56-87	Bt1	84.5	15.0	0.5	c	c	69
	87-112	Bt2	77.4	21.1	1.5	c	sic	72
	112-138	Bt2	64.7	31.4	3.9	c	sic	66
	138-185	BC	45.6	33.7	20.7	c	sic	64
Haiku	0-24	Ap1	47.8	40.6	11.6	sic	c	52
clay	24-47	Ap2	43.0	46.9	10.1	sic	c	55
	47-63	Bw	70.2	21.2	8.6	c	sic	64
	63-75	Bt	61.6	20.4	18.0	c	sic	66
	75-88	Bt/C	40.6	30.0	29.4	c	sic	66
	88-130	BC	39.2	38.8	22.0	cl	sic	66
	130-196	CB	25.5	43.0	31.2	l	sic	60
Pauwela	0-18	Ap1					c	58
clay	18-30	Ap2					c	60
	30-43	Bt1					c	84
	43-60	Bt2					c	88
	60-75	Bt3					c	90
	75-103	Bt/C					c	78
	103-138	C					sic	54
Hamakua-	0-26	Ap1	37.5	53.7	8.8	sicl	sic	58
poko	26-50	Ap2	40.0	53.2	6.8	sicl	sic	56
silty	50-72	Bw	9.5	29.3	61.2	sl	sic	86
clay	72-94	Bt/C	9.7	26.3	64.0	sl	sic	100+
	94-141	Cr	6.8	21.5	71.7	sl	rock	95
Makawao	0-16	Ap	26.8	69.5	3.7	sil	sic	51
silty	16-30	Bw	24.6	68.9	6.5	sil	sic	44
clay	30-51	Bt1	17.2	66.9	15.9	sil	sic	43
	51-74	Bt2	16.7	35.0	48.3	l	sic	52
	74-97	Bt2	12.0	24.6	63.4	sl	sic	53
	97-123	C/B	0.6	18.5	80.9	ls	sic	86
	123-153	Cr	3.7	22.3	74.0	ls	rock	100+

* c=clay, cl=clay loam, l=loam, ls=loamy sand, sic=silty clay, sicl=silty clay loam, sil=silt loam, sl=sandy loam.

** 2.5 x 1500-kPa water content in percent

The clay content values in Table 6 and the distribution curve in Figure 2 indicate the presence of an argillic horizon in all soils except the Makawao silty clay. These data also indicate a higher clay content in the argillic horizon of the Pauwela soil than in the others. The low clay content (pipette method) in the lower three horizons of the Hamakuapoko soil, together with the high P retention value ($>$ 85%) and pH (NaF) values of over 9.0, further suggests the occurrence of volcanic ash material in the lower portion of this soil.

The surface of the sampled Makawao soil appeared to be a deposited material from a higher landscape. Because this horizon further appeared to be only a plow layer over an argillic horizon, the subsurface horizons were considered to be an argillic horizon. Clay films were observed in the major part of this horizon.

Based on the estimated clay content, an increase in clay was noted in the subsurface horizons of the Makawao soil. Similar trends were also noted in another profile of the Makawao soil that was collected at an earlier date near the sample site (Ikawa et al, 1985).

All of the soils used in this study, therefore, have an argillic horizon.

4.2.2. Available water

Available water can be calculated from the 33-kPa and 1500-kPa water contents. The mean values for the upper three horizons of the lower elevation soils are 10 percent for the Haiku soils and 8.5 percent for the Pauwela clay. Similar values of the higher elevations are 8.4 percent for the Hamakuapoko silty clay and 13.4 percent for the Makawao silty clay.

4.2.3. Bulk density

The bulk density values range from 1.2 to 1.5 Mgm^{-3} for the Haiku soils, 1 to 1.2 Mgm^{-3} for the Pauwela silty clay, and 0.96 to 1.4 Mgm^{-3} for the Hamakuapoko silty clay, and 1.2 to 1.7 Mgm^{-3} for the Makawao silty clay. The lower values in the lower subsoil of the Hamakuapoko soil also suggest the presence of volcanic ash material in this soil.

These results so far indicate that the morphological properties of the surface soils, properties such as hue, wet consistence, and apparent texture (as influenced by aggregates) are directly related to soil formation as influenced by the climatic factor of rainfall, but physical properties such as clay content, available water content, and bulk density are related not only to rainfall but also the kind of parent material, for example, volcanic ash.

4.3 Chemical Properties (Tables 8, 10, 12, 14, and 16)

4.3.1. Organic C and total N

The mean organic C content of the surface two horizons of soils at the lower elevations ranges from 2.5 to 2.9 percent. The content of the Makawao and Hamakuapoko soils at the higher elevations are 2.9 and 4.1 percent, respectively. The mean total N of the same surface horizons, on the other hand, ranges from 0.18 and 0.24 percent for the lower elevations and are 0.28 and 0.34 for the Makawao and Hamakuapoko soils, respectively.

There is no great influence of the climatic factors to indicate that there is more organic C in the cooler and more moist environment within the study area. There is slightly more total N in the upper elevation soils (cooler environment) than in the lower elevation soils, but this may also be due to the influence of some volcanic ash material.

In contrast, in the surface horizon of the Waiakoa soil (Ustox) at 25-m elevation, with mean annual rainfall (MAR) of 250 mm, the organic C is 1.06 percent while the total N is 0.10 percent. In the Molokai soil (Torrox) at 57-m elevation, where the MAR is 540 mm, the organic C is 1.53 percent and the total N is 0.25 percent, while in the surface horizon of the Keahua soil (Ustox) at 375-m elevation, with 380 mm MAR, the organic C is 1.96 percent (SCS, 1984b).

4.3.2. Cation exchange capacity and base saturation

The cation exchange capacity (by ammonium acetate, pH 7.0) of the surface two horizons decreased from west to east, from low to high median annual rainfall, at the low as well as high elevations. Mean values of 16.9, 16.6, and 13.9 cmol$(p^+)kg^{-1}$ of soil were obtained for the two Haiku soils and the Pauwela soil, respectively, and 22.8 and 15.6 cmol $(p^+)kg^{-1}$ for the Hamakuapoko and Makawao soils, respectively. The base saturation of these same surface soils also decreased from a mean of 50 percent (Haiku silty clay) to 4 to 5 percent at the lower elevations and a mean of 28 to 14 percent at the higher elevations.

The 50 percent base saturation of the Haiku silty clay is exceptionally high, but this is only because the experimental site was once applied with coral lime as base material for construction purposes (J. Roskowski, personal communication). Table 8 shows a high content of exchangeable Ca throughout the solum of this particular soil.

4.3.3. Effective cation exchange capacity and aluminum saturation

Tables 8, 10, 12, 14 and 16 show that the effective cation exchange capacity (ECEC) ranges from about 1 to 10 cmol$(p^+)kg^{-1}$ in the two surface horizons of the lower elevation soils. The extractable Al ranges from 0 to 1.3 cmol $(p^+)kg^{-1}$. On the other hand, the ECEC ranges from 2.5 to 6.8 in the upper elevation soils where the extractable Al ranges from 0.1 to 1.4 cmol$(p^{+})kg^{-1}$.

Although there is no Al saturation in the Haiku silty clay, due to addition of the lime, the Al saturation ranges from 30 to 55 percent in the upper two soil horizons of the Haiku clay. This value ranges from 60 to 70 in the Pauwela soil. There is little or no Al in the Hamakuapoko soil but the content ranges from 0.8 to 1.4 cmol$(p^{+})kg^{-1}$ in the Makawao soil.

4.3.4. Extractable Fe and P retention

With increase in the median annual rainfall, there is also an increase in the extractable Fe. Phosphate retention also ranges from about 50 to 80 percent in most soils and as much as 100 percent in one horizon of one soil. The latter, the subsoil of the Hamakuapoko soil, appears to be associated with volcanic ash parent material.

The chemical properties indicate that with increase in the median annual rainfall, there are leaching or loss of the bases, increase in acidity including Al saturation, and increase in the extractable Fe. Associated with the soils is also moderate amount of P retention or fixation. These soils, with the exception of the limed Haiku soil, are infertile soils which will require much management input when used for crop production.

As indicated by Buol et al (1980), Foth and Schafter (1980), and Jones (1983), extensive leaching in Ultisols leads to soils with low base saturation, high acidity, rapid and complete alteration of weatherable minerals into secondary clay minerals or oxides including non-crystalline materials. Although the clay increase in the argillic horizon is associated with increase in rainfall and weathering, the need

Table 7. Morphological properties of Haiku silty clay (S84HA4-1).

Depth 10^{-2}m	Horizon	Color moist	Color dry	Texture	Structure grade	Structure size	Structure type	Consistence dry	Consistence moist	Consistence wet
0-28	Ap1	7.5YR 3/2	10YR 5/3	sic	3	f-vf	sbk	vh	vfi	vs,vp
28-43	AB	7.5YR 3/2,3/4		sic	3	vf	sbk	vh	fi	vs,vp
43-56	Bw	7.5YR 3/4		sic	3	f	abk	vh	fi	vs,vp
56-87	Bt1	5YR 3/3, 3/4		c	3	vf	abk	vh	fi	vs,vp
87-138	Bt2	7.5YR 3/3		sic	2	vf	abk		fi	vs,sp
138-185	BC	10YR 3/2		sic	2	f-m	sbk		fi	vs,vp

Depth 10^{-2}m	Roots	Pores	Cutans	Reaction (pH)	Boundary
0-28	3vf, 1co	3i		medium acid, 6.0	cs
28-43	3vf, 1co	3vf		medium acid, 6.0	cs
43-56	2vf	3vf, 1f		medium acid, 6.0	cw
56-87	1vf	2vf, 1m	2n pf&po	medium acid, 6.0	gw
87-138	1vf	3vf	2n pf&po	very strongly acid, 5.0	gw
138-185	1vf	3vf	1n pf&po	very strongly acid, 5.0	

Codes: Texture; sic= silty clay, c= clay. Structure; 2= moderate, 3= strong, f= fine, vf= very fine, m= medium, abk= angular blocky, sbk= subangular blocky. Consistence; vh= very hard, vfi= very firm, fi= firm, vs= very sticky, vp= very plastic. Roots; 1= few, 2= common, 3= many, vf= very fine, co= coarse. Pores; 2= common, 3= many, i= interstitial, vf= very fine, f= fine, m= medium Cutans; 2= common, 1= few, n= thin, pf= on ped faces, po= in pores. Boundary; cs= clear smooth cw= clear wavy, gw= gradual wavy.

Table 8. Physical and chemical properties of Haiku silty clay (S84HA4-1).

Depth	Horizon	Part. size analy.			Bulk density 33-kPa	Water content		Org. C	Total N	C/N	Extr. iron		P Retention
		clay	silt	sand		33-kPa	1500-kPa				Fe	Fe_2O_3	
$-10^{-2}m-$		--------%-------			$-Mgm^{-3}$	--------------%-------------					----------%------------		
0-28	Ap1	55.1	41.2	3.5	1.46	28.5	20.7	3.22	0.26	12	6.7	9.6	52
28-43	AB	60.4	38.1	1.5	1.40	32.2	22.2	2.29	0.21	11	7.7	11.0	58
43-56	Bw	78.5	20.7	0.8	1.37	33.4	26.3	1.89	0.20	9	10.3	14.8	69
56-87	Bt1	84.5	15.0	0.5	1.33	36.0	27.6	1.60	0.17	9	10.0	14.4	62
87-112	Bt2	77.4	21.1	1.5	1.31	36.2	28.6	1.23	0.13	9	10.9	15.6	61
112-138	Bt2*	64.7	31.4	3.9	1.31	35.4	26.5	1.14	0.10	11	9.0	12.9	72
138-185	BC	45.6	33.7	20.7	1.27	32.7	25.5	1.13	0.09	13	7.4	10.6	81

Depth	Extractable bases					Extr. acid	CEC		BS		Extr. Al	ECEC	Al Sat.	pH			
	Ca	Mg	Na	K	Sum		AAc	Sum	AAc	Sum				H_2O	KCl	dpH	NaF
$-10^{-2}m-$	----------------$cmol(p^+)kg^{-1}$---------------								----%---		$cmol(p^+)kg^{-1}$		-%-				
0-28	5.6	1.7	0.3	2.4	10.0	18.4	18.1	28.4	55	35	-	10.0	-	4.7	4.9	+.2	8.6
28-43	4.7	1.4	0.4	0.5	7.0	16.6	15.8	23.6	44	30	-	7.0	-	5.1	5.0	-.1	8.7
43-56	4.1	1.6	0.4	0.7	6.8	17.2	16.8	24.0	40	28	-	6.8	-	5.2	5.1	-.1	8.7
56-87	3.4	1.8	0.5	1.1	6.8	18.1	19.8	24.9	34	27	-	6.8	-	5.2	5.2	0	8.8
87-112	2.0	2.1	0.5	1.8	6.4	16.1	19.1	22.5	33	28	-	6.4	-	5.1	5.2	+.1	8.8
112-138	1.7	1.9	0.6	0.6	4.8	21.2	17.0	26.0	28	18	-	4.8	-	5.3	5.1	-.2	8.9
138-185	1.0	1.3	0.2	0.3	2.8	21.1	16.0	23.9	18	12	-	2.8	-	5.3	5.1	-.2	8.9

* split sample

Table 9. Morphological properties of Haiku clay (S84HA4-3).

Depth $-10^{-2}m-$	Horizon	Color moist	Color dry	Texture	Structure grade	Structure size	Structure type	Consistence dry	Consistence moist	Consistence wet
0-24	Ap1	7.5YR 4/4	7.5YR 7/4	c	3	vf-f	abk	vh	fi	vs,vp
24-47	Ap2	7.5YR 4/4	7.5YR 7/4	c	2	vf-m	sbk		fi	vs,vp
47-63	Bw	5YR 4/6		sic	1	f-m	sbk		fr	vs,vp
63-75	Bt	5YR 4/6		sic	2	vf-f	sbk		fr	vs,vp
75-88	Bt/C	5YR 4/4		sic	2	f-m	sbk		fr	vs,vp
88-130	BC	7.5YR 4/4		sic	1	f-m,	sbk		fr	vs,vp
					2	vf-f				
130-196	CB	7.5YR 3/4		sic	2	f-m	sbk		fr	s,p

Depth $-10^{-2}m$	Roots	Pores	Cutans	Reaction (pH)	Boundary
0-24	3vf, 3f	3 i		very strongly acid, 5.0	cs
24-47	2vf, 2f	3vf		extremely acid, 4.4	cw
47-63	2vf	3vf, 1f		very strongly acid, 4.5	cw
63-75	1vf	3vf	2n pf&po	very strongly acid, 4.5	cw
75-88	1vf	3vf	2mk pf&po	very strongly acid, 5.0	cw
88-130	1vf	3vf	2mk pf&po	very strongly acid, 5.0	ci
130-196		3vf, 1f	1mk	very strongly acid, 5.0	

Codes: Texture; c= clay, sic= silty clay. Structure; 1= weak, 2= moderate, 3= strong, f= fine, vf= very fine, m= medium, abk= angular blocky, sbk= subangular blocky. Consistence; vh= very hard, fi= firm, fr= friable, vs= very sticky, vp= very plastic, s= sticky, p= plastic. Roots; 1= few, 2= common, 3= many, vf= very fine, f= fine. Pores; 1= few, 3= many, i= interstitial, vf= very fine, f= fine. Cutans; 1= few, 2= common, n= thin, mk= moderately thick, pf= on ped faces, po= in pore Boundary; cs= clear smooth, cw= clear wavy, ci= clear irregular.

Table 10. Physical and chemical properties of Haiku clay (S84HA4-3).

Depth	Horizon	Part. size analy. clay	silt	sand	Bulk density 33-kPa	Water content 33-kPa	1500-kPa	Org. C	Total N	C/N	Extr. iron Fe	Fe_2O_3	P Retention
$-10^{-2}m-$		--------%-------			$-Mgm^{-3}$	---------------%-------------					-----------%---------		
0-24	Ap1	47.7	40.6	11.6	1.47	29.5	20.9	2.92	0.19	15	8.9	12.8	62
24-47	Ap2	43.0	46.9	10.1	1.37	33.2	22.0	2.14	0.17	13	9.6	13.7	72
47-63	Bw	70.2	21.2	8.6	1.15	41.1	25.6	2.26	o.17	13	20.0	28.7	82
63-75	Bt	61.6	20.4	18.0	1.23	38.0	26.5	2.48	0.17	15	16.5	23.6	84
75-88	Bt/C	40.6	30.0	29.4	1.22	40.1	26.5	1.71	0.10	17	9.9	14.1	81
88-130	BC	39.2	38.8	22.0	1.35	34.8	26.3	1.11	0.07	16	9.5	13.6	76
130-196	CB	25.8	43.0	31.2	1.29	35.7	23.8	1.18	0.05	24	9.7	13.8	79

Depth	Extractable bases Ca	Mg	Na	K	Sum	Extr. acid	CEC AAc	Sum	BS AAc	Sum	Extr. Al	ECEC	Al Sat.	pH H_2O	KCl	dpH	NaF
$-10^{-2}m-$	-----------------$cmol(p^+)kg^{-1}$-----------------								----%---		$cmol(p^+)kg^{-1}$		-%--				
0-24	0.29	0.34	0.13	0.35	1.1	16.2	17.0	17.3	6	6	0.41	1.5	27	5.1	4.0	-1.1	8.8
24-47	0.10	0.08	0.11	0.14	0.43	19.7	16.1	20.1	3	2	0.48	0.9	53	4.9	4.1	- .8	8.8
47-63	0.10	0.11	0.15	0.27	0.63	23.7	20.8	24.3	3	3	0.55	1.2	47	4.8	4.1	- .7	8.8
63-75	0.15	0.18	0.19	0.31	0.83	22.0	21.0	22.8	4	4	0.35	1.2	30	4.8	4.2	- .6	8.8
75-88	0.27	0.40	0.40	0.72	1.8	22.1	18.2	23.9	10	8	0.36	2.2	17	5.0	4.3	- .7	8.8
88-130	0.36	0.43	0.20	0.88	1.9	21.3	16.0	23.2	12	8	0.75	2.7	28	5.1	4.2	- .9	9.0
130-196	0.26	0.29	0.16	0.29	1.0	20.7	14.9	21.7	7	5	0.97	2.0	49	5.0	4.0	-1.0	9.0

Table 11. Morphological properties of Pauwela clay (S62HA4-4).

Depth $-10^{-2}m-$	Horizon	Color moist	Color dry	Texture	Structure grade	Structure size	Structure type	Consistence dry	Consistence moist	Consistence wet
0-18	Ap1	2.5Y 4/2	2.5Y 5/2	c	3	vf-f	sbk	h	fi	s , p
					3	vf-f	gr			
18-30	Ap2	2.5Y 4/2	2.5Y 5/2	c	2	vf-f	sbk	sh	fr	s , p
30-43	Bt1	5YR 4/6	5YR 5/6	c	1	f-m	sbk	so	fr	s , p
43-60	Bt2	5YR 4/6	5YR 5/6	c	3	vf-f	abk	sh	fi	s , p
60-75	Bt3	5YR 3/4		c	2-3	vf-f	abk	sh	fi	s , p
75-103	Bt/C	5YR 3/4		c	2-3	vf-f	abk	sh	fr	s , p
103-138	C	7.5YR 4/4,5/6		sic	1	vf-f	sbk	so	fr	ss,ps

Depth $-10^{-2}m-$	Roots	Pores	Cutans	Reaction (pH)	Boundary
0-18	3	2vf, 2f t, 3 i		very strongly acid, 5.0	cw
18-30	3	2vf, 2f, 1m, 1co t		very strongly acid, 4.8	aw
30-43	2	3vf, 3f, 1m t	2n pf	very strongly acid, 4.5	gw
43-60	2	3vf, 3f, 1mt	2mk pf&po	very strongly acid, 4.6	gw
60-75	1	2vf, 2f t	2mk pf&po	very strongly acid, 4.6	gw
75-103	1	2vf, 2f, 1m t		very strongly acid, 4.6	gw
103-138		3vf t		very strongly acid, 4.7	

Codes: Texture; sic= silty clay, c= clay. Structure; 1= weak, 2= moderate, 3= strong, f= fine, vf= very fine, m= medium, abk= angular blocky, sbk= subangular blocky, gr= granular. Consistence; h= hard sh= slightly hard, so= soft, fi= firm, fr= friable, s= sticky, p= plastic, ss= slightly sticky, ps= slightly plastic. Roots; 1= few, 2= common, 3= many. Pores; 1= few, 2= common, 3= many, vf= very fine, f= fine, i= interstitial, t= tubular, m= medium, co= coarse. Cutans; 2= common, n= thin, mk= moderately thick, pf= on ped faces, po= in pores. Boundary; cw= clear wavy, aw= abrupt wavy, gw= gradual wavy.

Table 12. Physical and chemical properties of Pauwela clay (S62HA4-4).

Depth	Horizon	Part. size analy. clay	silt	sand	Bulk density f. moist	Water content 33-kPa	1500-kPa	Org. C	Total N	C/N	Extr. iron Fe	Fe_2O_3	P Retention
$-10^{-2}m-$		-------%--------			$-Mgm^{-3}$	---------------%------------					-----------%------------		
0-18	Ap1				1.14	30.5	23.1	2.88	0.23	13	15.3	21.9	
18-30	Ap2				1.14	31.8	24.0	2.86	0.20	14	15.4	22.0	
30-43	Bt1				1.05	43.9	33.5	2.58	0.15	17	24.6	35.2	
43-60	Bt2				1.10	41.2	35.4	1.66	0.11	15	30.9	44.2	
60-75	Bt3				1.23	40.3	35.8	1.68	0.11	15	27.1	38.7	
75-103	Bt/C				1.20	36.6	31.2	0.82			16.7	23.9	
103-138	C				1.18	29.7	21.5	0.61			12.9	18.4	

Depth	Extractable bases Ca	Mg	Na	K	Sum	Extr. acid	CEC AAc	CEC Sum	BS AAc	BS Sum	Extr. Al	ECEC	Al Sat.	pH H_2O	KCl	dpH	NaF
$-10^{-2}m-$	------------------$cmol(p^+)kg^{-1}$------------								----%---		$cmol(p^+)kg^{-1}$		-%--				
0-18	-	0.6	0.1	0.2	0.9		14.5		6		1.3	2.2	59	5.0	3.8	-1.2	
18-30	-	0.2	0.1	0.2	0.5		13.3		4		1.3	1.8	72	4.5	3.8	-1.0	
30-43	-	-	0.1	0.1	0.2		13.6		1		1.5	1.7	88	4.5	4.0	- .5	
43-60	-	0.1	0.1	0.1	0.3		12.8		2		0.3	0.6	50	4.6	4.2	- .4	
60-75	-	0.3	0.1	0.1	0.5		11.9		4		0.3	0.8	36	4.6	4.2	- .4	
75-103	0.3	0.1	0.5	0.3	1.2		8.0		15		0.6	1.8	33	4.6	4.0	- .6	
103-138	0.2	0.1	0.4	0.5	1.2		5.9		20		0.5	1.7	29	4.7	4.0	- .7	

Source: Soil Survey Investigation Report No. 29 (SCS, 1976)

Table 13. Morphological properties of Hamakuapoko silty clay (S84HA4-4).

Depth $-10^{-2}m-$	Horizon	Color		Texture	Structure			Consistence		
		moist	dry		grade	size	type	dry	moist	wet
0-26	Ap1	7.5YR 3/2	7.5YR 5/4	sic	3	vf-f	sbk	vh	fi	vs,vp
26-50	Ap2	7.5YR 3/2		sic	1	vf-m	sbk	vh	fi	vs,vp
50-72	Bw	5YR 4/6		sic	1	f-m	sbk		fr	vs,vp
72-94	Bt/C	5YR 4/6, 7.5YR 4/6		sic	3	vf-f	sbk		vfi	s,p
94-141	Cr	10YR 6/1	hard weathered rock							

Depth $-10^{-2}m-$	Roots	Pores	Cutans	Reaction (pH)	Boundary
0-26	3vf, 1f	3 i		medium acid, 6.0	cw
26-50	3vf, 1f	3vf		medium acid, 6.0	cw
50-72	2vf, 1f	3vf	1n	medium acid, 6.0	ci
72-94	1vf, 1f	3vf	2mk	medium acid, 6.0	cw
94-141	-	-	-	-	

Codes: Texture; sic= silty clay. Structure; 1= weak, 3= strong, vf= very fine, f= fine, m= medium, sbk= subangular blocky. Consistence; vh= very hard, fi= firm, fr= friable, vfi= very firm, vs= very sticky, sp= very plastic, s= sticky, p= plastic. Roots; 1= few, 2= common, 3= many, vf= very fine. f= fine. Pores; 3= many, vf= very fine, i= interstitial. Cutans; 1= few, 2= common, n= thin, mk= moderately thick. Boundary; cw= clear wavy, ci= clear irregular.

Table 14. Physical and chemical properties of Hamakuapoko silty clay (S84HA4-4).

Depth	Horizon	Part. size analy.			Bulk	Water content		Org.	Total	C/N	Extr. iron		P
		clay	silt	sand	density	33-kPa	1500-kPa	C	N		Fe	Fe_2O_3	Retention
-10^{-2}m-		--------%-------			$-Mgm^{-3}$	----------------%---------------					-----------%------------		
0-26	Ap1	37.5	53.7	8.8	1.26	31.6	23.1	4.82	0.39	12	8.8	12.6	75
26-50	Ap2	40.0	53.2	6.8	1.38	30.6	22.4	3.39	0.30	11	8.5	12.2	73
50-72	Bw	9.5	29.3	61.2	0.999	59.7	34.6	3.29	0.32	10	11.7	16.7	94
72-94	Bt/C	9.7	26.3	64.0	0.956	61.9	43.2	4.60	0.37	12	11.0	15.7	98
94-141	Cr	6.8	21.5	71.7			37.9	2.86	0.17	17	6.2	8.9	99

Depth	Extractable bases					Extr.	CEC		BS		Extr.	ECEC	Al	pH			
	Ca	Mg	Na	K	Sum	acid	AAc	Sum	AAc	Sum	Al		Sat.	H_2O	KCl	dpH	NaF
-10^{-2}m	----------------$cmol(p^+)kg^{-1}$----------------								----%---		$cmol(p^+)kg^{-1}$		-%--				
0-26	3.6	1.3	0.30	0.95	6.2	18.5	22.9	24.7	27	25	0.1	6.3	2	4.8	4.2	-.6	9.0
26-50	5.0	0.9	0.37	0.51	6.8	18.0	22.7	24.8	30	27	-	6.8	-	5.0	4.4	-.6	9.0
50-72	9.6	1.6	0.25	0.67	12.2	27.4	39.4	39.6	31	31	-	12.2	-	5.0	4.6	-.4	9.2
72-94	10.8	1.9	0.26	0.34	13.3	27.8	46.2	41.1	29	32	-	13.3	-	5.2	4.8	-.4	10.3
94-141	5.1	1.5	0.39	0.43	7.4	23.6	38.1	31.0	19	24	-	7.4	-	5.3	4.9	-.4	9.8

Table 15. Morphological properties of Makawao silty clay (S83HA4-12).

Depth $-10^{-2}m-$	Horizon	Color		Texture	Structure			Consistence		
		moist	dry		grade	size	type	dry	moist	wet
0-16	Ap	5YR 3/3	5YR 5/4	sic	3	vf-f	sbk	vh	fi	vs,vp
16-30	Bw	5YR 3/3	5YR 5/4	sic	1	f-m	sbk	vh	fi	s,p
30-51	Bt1	2.5YR 3/4	2.5YR 4/4	sic	2	vf-f	sbk	vh	fi	vs,vp
51-97	Bt2	2.5YR 3/4, 3/6	2.5YR 4/4	sic	3	vf-f	sbk	vh	fi	vs,vp
97-123	C/B	2.5YR 3/4, 3/6	2.5YR 5/6	sic	3	vf-f	sbk	vh	fi	s,p
123-153	Cr	10YR 3/1, 5/5		hard weathered rock						

Depth $-10^{-2}m-$	Roots	Pores	Cutans	Reaction (pH)	Boundary
0-16	3vf	3vf		very strongly acid, 5.0	cs
16-30	3vf	3vf		very strongly acid, 5.0	gw
30-51	3vf	3vf	1n	very strongly acid, 5.0	cw
51-97	2vf	3vf	2mk pf&po	very strongly acid, 5.0	cs
97-123	1vf	3vf	1n pf&po		cs
123-153	-	-	-	-	

Codes:Texture; sic= silty clay. Structure; 1= weak, 2= moderate, 3= strong, vf= very fine, f= fine m= medium. sbk= subangular blocky. Consistence; vh= very hard, fi= firm, vs= very sticky, vp= very plastic, s=sticky, p= plastic. Roots; 1= few, 2= common, 3= many, vf= very fine. Pores; 3= many, vf= very fine. Cutans; 1= few, 2= common, n= thin, mk= moderately thick, pf= on ped faces, po= in pores. Boundary; cs= clear smooth, gw= gradual wavy, cw= clear wavy.

Table 16. Physical and chemical properties of Makawao silty clay (S83HA4-12).

Depth	Horizon	Part.size analy.			Bulk density 33-kPa	Water content		Org. C	Total N	C/N	Extr. iron		P Retention
		clay	silt	sand		33-kPa	1500-kPa				Fe	Fe_2O_3	
$-10^{-2}m-$		-------%--------			Mgm^{-3}	--------------%--------------					-----------%----------		
0-16	Ap	26.8	69.5	3.7	1.17	38.8	20.4	3.58	0.336	11	16.0	22.9	64
16-30	Bw	24.6	68.9	6.5	1.33	31.6	17.8	2.22	0.231	10	16.1	23.0	58
30-51	Bt1	17.2	66.9	15.9	1.65	25.4	17.3	1.30	0.110	12	18.0	25.7	48
51-74	Bt2	16.7	35.0	48.3	1.61	28.5	20.6	0.98			18.9	27.0	57
74-97	Bt2*	12.0	24.6	63.4	1.68	29.0	21.1	0.88	0.071	12	18.4	26.3	56
97-123	C/B	0.6	18.5	80.9	1.7		34.3	3.14					
123-153	Cr	3.7	22.3	74.0			48.1	1.75			3.9	5.6	100

Depth	Extractable bases					Extr. acid	CEC		BS		Extr. Al	ECEC	Al Sat.	pH			
	Ca	Mg	Na	K	Sum		AAc	Sum	AAc	Sum				H_2O	KCl	dpH	NaF
$-10^{-2}m-$	-----------------$cmol(p^+)kg^{-1}$---------------								---%----		$cmol(p^+)kg^{-1}$		-%-				
0-16	2.7	0.7	0.2	0.1	3.7	28.9	18.1	32.6	20	11	0.8	4.5	18	5.1	4.3	-.8	8.6
16-30	0.7	0.1	0.3	tr.	1.1	27.4	13.1	28.5	8	4	1.4	2.5	56	4.8	4.1	-.7	8.8
30-51	0.4	0.1	0.1	-	0.6	22.9	11.0	23.5	5	3	1.0	1.6	63	4.5	3.9	-.6	8.2
51-74	0.8	0.1	0.2	-	1.1	23.1	9.8	24.2	11	5	0.5	1.6	31	4.7	3.9	-.8	8.1
74-97	0.5	0.1	0.1	-	0.7	22.4	9.5	23.1	7	3	0.6	1.3	46	4.7	4.1	-.6	8.3
97-123	0.4	0.1	0.2	tr.	0.7	55.3	42.9	56.0	2	1		0.7					
123-153	-	tr.	0.2	-	0.2	52.6	42.9	52.8	tr.	tr.	0.6	0.8	75				11.0

* split sample

for an alternating wet and dry condition in the subsoil is recognized (Eswaran, 1979). Rainfall data for Hawaii show rainy periods to be generally from November to April with less rainfall during the other months.

4.4 Classification of Soils

Based on the morphological properties (Tables 7, 9, 11, 13, and 15) and the chemical and physical properties (Tables 8, 10, 12, 14, and 16), the soils of the study area are classified as Ultisols. According to the key to the soil orders (Soil Survey Staff, 1975), these soils have neither the high organic matter nor the presence of spodic horizon, oxic horizon, cracking and related properties or an aridic moisture regime to be classified as Histosols, Spodosols, Oxisols, Vertisols, or Aridisols.

Furthermore, the soils used in this study have an argillic horizon and other properties such as a base saturation less than 35 percent (by sum of cations) at the prescribed depth to be classified as Ultisols. Because they have 0.9 percent or more organic C in the upper 15 cm of the argillic horizon, they are classified in the suborder Humults.

Because the clay content in the argillic horizon of the Haiku soils and the Pauwela soil decrease by more than 20 percent of the maximum amount of clay within 1.5 m of the soil surface and because they have an iso-soil temperature regime, these soils are further classified as Tropohumults. On the other hand, there is no such clay decrease in the Hamakuapoko and Makawao soils and they are classified as Palehumults.

4.4.1. Haiku silty clay and Haiku clay

Tables 8 and 10 show that the CEC (by ammonium acetate) in the argillic horizon ranges from about 16 to 20 or 21 $cmol(p^{+})kg^{-1}$ of soil in both of the Haiku soils. When these values are expressed as $cmol(p^{+})$

kg^{-1} of clay, all or a major part of the argillic horizon is more than 24 $cmol(p^+)kg^{-1}$ of clay.

Because the CEC is more than 24 $cmol(p^+)kg^{-1}$ of clay in the major part of the argillic horizon, both of the Haiku soils are classified as Typic Tropohumults. Their high clay content (over 35 percent), high Fe oxide content, and a mean annual temperature (MAT) of over 22 C, further classify them as being members of the clayey, oxidic, isohyperthermic family of Typic Tropohumults.

According to the proposal of the International Committee on Classification of Soils of Low Activity Clays (ICOMLAC), the Haiku soils have a kandic horizon. The kandic horizon is a subsurface horizon with either a cation exchange capacity (CEC) of less than 16 $cmol(p^+)kg^{-1}$ of clay (by ammonium acetate) or an effective cation exchange capacity (ECEC) of less than 12 $cmol(p^+)kg^{-1}$ of clay. Although the Haiku soils do not meet the 16 cmol CEC requirement, they meet the ECEC requirement.

Using the ICOMLAC taxonomic key, the Haiku soils are classified as Kanhaplohumults because they have a clay distribution such that the clay percentage decreases from its maximum amount by as much as 20 percent within a depth of 1.5 m from the soil surface. They are further classified as being members of the clayey, oxidic, isohyperthermic family of Typic Kanhaplohumults.

The family classification of this soil and those of the others according to Soil Taxonomy and the ICOMLAC proposal are summarized in Table 17.

4.4.2. Pauwela clay

In contrast to the Haiku soils, the Pauwela clay has a lower CEC (Table 12). When expressed on the basis of clay content, the CEC is less than 24 $cmol(p^+)kg^{-1}$ of clay in the major part of the horizon, and because the soil is never dry in any part of the moisture control section in most years, the Pauwela clay is classified as Humoxic Tropohumults. It is further a member of the clayey, oxidic, isohyperthermic family.

According to the ICOMLAC proposal, the Pauwela clay is also classified as Typic Kanhaplohumults. This soil, however, is characterized by having both a CEC of less than 16 cmol and an ECEC of less than 12 $cmol(p^+)kg^{-1}$ of clay. It is also a member of the clayey, oxidic, isohyperthermic family.

4.4.3. Hamakuapoko silty clay

In contrast to the Haiku and Pauwela soils, the Hamakuapoko silty clay has a higher CEC (Table 14). When expressed on the basis of clay content, the CEC of the argillic horizon is about 46 $cmol(p^+)kg^{-1}$ of clay. This high CEC, together with the high P retention (over 90 percent), high pH in NaF solution (over 9.0), low bulk density (less than 1.0 Mgm^{-3}), support the idea that this soil has had the influence of volcanic ash material.

Whereas the Pauwela clay is a low activity clay soil, the Hamakuapoko silty clay is a high activity clay soil, and the presence of amorphous material in volcanic ash material can be associated with the high activity. The Hamakuapoko soil, thus, has properties almost similar to andeptic soils. It is, however, more weathered or more developed than such soils and it may be a transitional soil between an Inceptisol and Ultisol.

Nevertheless, the Hamakuapoko silty clay is classified as Palehumults. It is further classified as Typic Palehumults because the CEC is more than 24 $cmol(p^+)kg^{-1}$ of clay, and it is classified as a member of the clayey, mixed, isohyperthermic family.

According to the ICOMLAC proposal, the Hamakuapoko silty clay does not have a kandic horizon and it is classified as a Haplohumult. Although the bulk density is lower than the other Ultisols, it is still higher than 0.95 Mgm^{-3} and, therefore, the Hamakuapoko soil is classified as Typic Haplohumults. The family classification remains as clayey, mixed, isohyperthermic.

4.4.4. Makawao silty clay

The Makawao soil also has a high CEC (Table 16), although not as high as that in the Hamakuapoko soil. When expressed on kg of clay, the CEC ranges from 18 to 25 $cmol(p^+)kg^{-1}$ in the argillic horizon. The CEC, however, is less than 24 $cmol(p^+)kg^{-1}$ of clay in the major part of the argillic horizon. The Makawao soil, therefore, is classified as Humoxic Palehumults. It is further a member of the clayey, oxidic, isothermic family.

According to the ICOMLAC proposal, this soil is classified as Typic Kandihumults because the ECEC in the argillic horizon is less than 12 $cmol(p^+)kg^{-1}$ of clay and because the clay decrease in the argillic horizon does not decrease from its maximum by more than 20 percent within the prescribed soil depth. It is also classified as being a member of the clayey, oxidic, isothermic family.

Table 17 shows the taxanomic classification of the Haiku, Pauwela, Hamakuapoko, and Makawao soil series as reported by the SCS (1981). This table also shows the classification of the sampled Haiku,

Table 17. Classification of soils of Maui study.

Location	Series	Soil Taxonomy		ICOMLAC Classification	
		SCS, 1981	This study	Proposal	Recommendation
Pauwela (NifTAL)	Haiku (S84HA4-1)	Humoxic Tropohumults clayey, ferritic, isohyperthermic	Typic Tropohumults clayey, oxidic, isohyperthermic	Typic Kanhaplohumults clayey, oxidic, isohyperthermic	Typic Haplohumults clayey, oxidic, isohyperthermic
Kuiaha (NifTAL)	Haiku (S84HA4-3)	Humoxic Tropohumults clayey, ferritic, isohyperthermic	Typic Tropohumults clayey, oxidic, isohyperthermic	Typic Kanhaplohumults clayey, oxidic, isohyperthermic	Typic Haplohumults clayey, oxidic, isohyperthermic
Ulumalu	Pauwela (S62HA4-4)	Humoxic Tropohumults clayey, oxidic, isohyperthermic	Humoxic Tropohumults clayey, oxidic, isohyperthermic	Typic Kanhaplohumults clayey, oxidic, isohyperthermic	Typic Kanhaplohumults clayey, oxidic, isohyperthermic
Haliimaile	Hamakuapoko (S84HA4-4)	Orthoxic Tropohumults clayey, oxidic, isohyperthermic	Typic Palehumults clayey, mixed, isohyperthermic	Typic Haplohumults clayey, mixed, isohyperthermic	Typic Haplohumults clayey, mixed, isohyperthermic
Makawao	Makawao (S83HA4-12)	Humoxic Tropohumults clayey, oxidic, isothermic	Humoxic Palehumults clayey, oxidic, isothermic	Typic Kandihumults clayey, oxidic, isothermic	Typic Haplohumults clayey, oxidic, isothermic

Hamakuapoko, and Makawao soils as determined by this study. Although the latter classification differs, there is no recommendation made to change the original classification because the sample soils may not have been representative samples in the mapped area. The taxonomic classification, as obtained in this study, is therefore the classification of the particular soil sample in the mapped area.

4.4.5. Recommended revision to ICOMLAC proposal (1984)

Table 17 shows the taxonomic classification according to the ICOMLAC proposal. This table also shows a recommended revised classification to the same soils.

According to the ICOMLAC proposal, soils having a kandic horizon must have a subsurface horizon with EITHER a cation exchange capacity (CEC) of less than 16 cmol$(p^+)kg^{-1}$ of clay (by ammonium acetate) OR an effective cation exchange capacity (ECEEC) of less than 12 cmol$(p^+)kg^{-1}$ of clay.

The recommendation here is to change the definition of the kandic horizon so that it is a subsurface horizon having BOTH a cation exchange capacity (CEC) of less than 16 cmol$(p^+)kg^{-1}$ of clay (by ammonium acetate) AND an effective cation exchange capacity (ECEC) of less than 12 cmol(p^+) kg^{-1} of clay.

In making this recommendation, a comparison of the Ultisols of Hawaii and Indonesia is made. In general, many of the Ultisols of Hawaii have a CEC of more than 16 cmol$(p^+)kg^{-1}$ of clay but with an ECEC of less than 12 cmol$(p^+)kg^{-1}$ of clay. By contrast, many of the Ultisols of Sumatra, Indonesia, have a CEC of less than 16 cmol$(p^+)kg^{-1}$ of clay and an ECEC of less than 12 cmol$(p^+)kg^{-1}$ of clay.

One of the major constraints in using Ultisols for crop production is the low nutrient retention capacity and the high Al saturation. The data in Tables 10, 12, 14, and 16 show that the four Ultisols of the Maui area have an Al sturation ranging from less than 5 to about 70 percent in the near surface soil horizons. By contrast, many of the Ultisols of Sumatra, Indonesia, have Al saturation ranging from 60 to about 90 percent in the near surface soil horizons (for example, the Abai Siat and Rimbo Bujang soils).

According to the ICOMLAC proposal, these two kinds of contrasting Ultisols are classified similarly. Yet, from the standpoint of management for crop production, these Ultisols are quite different. The Ultisols of Hawaii are "much better" soils than many of the infertile Ultisols of Sumatra, Indonesia. As an example, the suitability of some of the Ultisols of Hawaii for fuelwood tree production will be presented in the next section.

4.5 Land Use Potentials

The present land use of the study area is largely for pineapples, pasture, and homesites. Based on the soil characteristics and other environmental factors, there are other land use possibilities that can be suited for these areas; namely, the production of leucaena and eucalyptus for fuelwood. Presently, a local sugar plantation has the capacity to use not only bagassee, a waste product of sugarcane after the extraction of sugar, but also wood chips for the production of energy. In many tropical countries, giant leucaena provides a highly economical fuelwood and leaf meal (Ruskin, 1977; Brewbaker, 1980).

In assessing the physical land use potential of soils, crop requirements are matched with soil characteristics and climate conditions. Soil characteristics can be obtained from laboratory studies, but much of this information may also be derived from soil taxonomic names. For example, Cagauan et al. (1982) have extracted soil information from taxonomic names in recommending the use of leucaena and eucalyptus for agroforestry and fuelwood production.

The requirements of leucaena and eucalyptus were summarized in an earlier section (Materials and Methods). The environmental factors and the characteristics of the four soil series representing the five soils used in this study are also summarized in Table 18.

Matching the tree requirements with the soil and environmental characteristics shows that Leucaena leucocephala is not suited in the four soil series because of lack of exchangeable Ca or the presence of aluminum (Al saturation) and because of the isothermic temperature regime in the Makawao soil. This species, however, may be slightly or moderately suitable in the isohyperthermic Haiku, Pauwela, and Hamakuapoko soils with the application of lime to add the Ca or to correct the Al saturation. Soil depth of less than two meters is not critical to leucaena because it can adapt itself in thin, rocky soils, vertical cliffs, rock walls, and coral soils. Factors such as acidic soil layer or a layer with a high Al content, however, can hinder root penetration of leucaena (Ruskin, 1977).

The suitability rating of the soils for leucaena is summarized in Table 19.

Further matching of the data shows that the four soil series in the northern area of East Maui is suited for the production of eucalyptus. According to the requirments of eucalyptus (Materials and Methods), E. grandis may be better suited to the lower elevation soils such as the

Table 18. Environmental factors and characteristics of Haiku, Pauwela, Hamakuapoko, and Makawao soil series.

	Haiku	Pauwela	Hamakuapoko	Makawao
Elevation (m)	1-360	50-450	150-500	400-800
Annual rainfall (mm)	1250-1900	1750-3000	1000-1500	1500-2250
Soil temperature regime	isohyperthermic	isohyperthermic	isohyperthermic	isothermic
Soil pH *	4.7-5.1	4.5-5.0	4.8-5.0	4.8-5.1
Extractable Ca * ($cmol(p^+)kg^{-1}$)	0.1-0.3	nil	3.6-5.0	0.7-2.7
Estimated Al saturation * (percent)	30-55	60-70	2	20-60
Soil texture	silty clay to clay	clay	silty clay	silty clay
Soil drainage	well	well	well	well
Soil depth	deep	deep	deep	deep
Slope	gently to moderately sloping	gently to moderately sloping	gently to moderately sloping	gently to moderately sloping

* surface two horizon, from this study.

Haiku and Pauwela series, while E. globulus may be better suited to the higher elevation soils such as the Hamakuapoko and Makawao series. Suitability is also determined by the rainfall distribution associated with each of the soil series. Field examination of the soils shows that some of the soils have shallow soil depth. For such cases, on-site investigation must be made to down-grade the suitability for the production of the eucalyptus.

The suitability rating of the soil series for eucalyptus is also summarized in Table 19.

Table 19. The land suitability of leucaena and eucalyptus for fuelwood production.

Soil series	Leucaena leucocephala currently	Leucaena leucocephala after improvement	Eucalyptus grandis	Eucalyptus globulus
Haiku	not suitable	"slightly" to "moderately" suitable	"highly" suitable	"moderately" suitable
Pauwela	not suitable	"slightly" to "moderately" suitable	"highly" suitable	"moderately" suitable
Hamakuapoko	not suitable	"slightly" to "moderately" suitable	"moderately" suitable	"highly" suitable
Makawao	not suitable	not suitable	"moderately" suitable	"highly" suitable

SUMMARY AND CONCLUSIONS

Five Ultisols in the northern part of East Maui were selected to study their genesis, classification, and land use potential. At the lower elevations (120 to 280m), with the median annual rainfall increasing from 1450 mm on the west to 2500 mm on the east, the soils were the Haiku silty clay, Haiku clay, and Pauwela clay. At the higher elevations (350 to 640 m), with the median annual rainfall increasing from 1300 mm on the west to 1800 on the east, the soils were the Hamakuapoko silty clay and Makawao silty clay.

The geology of the study area is andesitic lava (Kula volcanic series) underlain by basaltic lava (Honomanu volcanic series). Several cinder cones, the source of volcanic ash, are associated with the Kula volvanic series. Thus, the dominant soil forming factors are climate and parent material. The objectives were to study the influence of these factors on soil formation, to verify the classification, and to determine the land-use potential.

The study showed that morphological properties such as hue, consistence, and apparent texture are influenced by increasing rainfall, but physical properties such as clay content, available water, and bulk density are related not only to rainfall but also to parent material. Chemical properties also change due to the influence of rainfall. With increase in rainfall, there were leaching or loss of the bases, increase in acidity including Al saturation, increase in extractable Fe, and increase in the oxides Fe and Al with associated P retention.

These changes in properties are associated with soils classified as Ultisols. The Haiku silty clay and Haiku clay are classified as Typic Tropohumults, clayey, oxidic, isohyperthermic (Typic Kanhaplohumults, according to ICOMLAC proposal); the Pauwela clay is Humoxic Tropohumults, clayey,oxidic, isohyperthermic (Typic Kanhaplohumults); while the Hamakuapoko silty clay is classified as Typic Palehumults, clayey,mixed, isohyperthermic (Typic Haplohumults). The Makawao silty clay, on the other hand, is classified as Humoxic Palehumults, clayey, oxidic, isothermic (Typic Kandihumults).

Recommendation is made to change the definition of the kandic horizon of the ICOMLAC proposal so that it is a subsurface horizon having BOTH a cation exchange capacity of less than 16 $cmol(p^+)kg^{-1}$ of clay (by ammonium acetate) AND an effective cation exchange capacity of less than 12 $cmol(p^+)kg^{-1}$ of clay. According to the ICOMLAC proposal, many of the Ultisols of Hawaii and that of Sumatra, Indonesia, will be classified similarly. Yet most of the Ultisols of Hawaii have a higher nutrient holding capacity and a lower Al saturation that many of the Ultisols of Indonesia.

The growth requirements of leucaena and eucalyptus for fuelwood tree production were matched with the soil series representing the soils used in this study. The matching showed that the Haiku, Pauwela, Hamakuapoko, and Makawao soils are not suited for the production of leucaena because of low exchangeable Ca or high Al saturation. With this limitation corrected with liming, the Haiku, Pauwela and Hamakuapoko soils can be upgraded to "slightly" to "moderately" suited for leucaena. The Makawao soil remains not suited even if limed because of its isothermic temperature regime.

The four soil series are better suited for the production of eucalyptus, with E. grandis being better suited to the lower elevation soils such as the Haiku and Pauwela soil series and E. globulus being better suited to the higher elevation soils such as the Hamakuapoko and Makawao soils.

APPENDIX A

Soil Profile Descriptions.

1. Haiku silty clay series (S84HA4-1).

Horizon	Descriptions
Ap1	0-28 cm; dark brown (7.5YR 3/2) silty clay; brown (10YR 5/3) dry; strong fine and very fine subangular blocky structure; very hard; very firm, very sticky, very plastic; many very fine and few coarse roots; many interstitial pores; medium acid (pH 6.0); clear smooth boundary.
AB	28-43 cm; dark brown (mixture of 7.5YR 3/2 and 3/4) silty clay; strong very fine subangular blocky structure with some clods; very hard, firm, very sticky, very plastic; many very fine and few coarse roots; many very fine pores; medium acid (pH 6.0); clear smooth boundary.
Bw	43-56 cm; dark brown (7.5 YR 3/4) silty clay; strong fine and medium angular blocky structure; very hard, firm, very sticky, very plastic; common very fine roots; many very fine and few fine pores; medium acid (pH 6.0); clear wavy boundary.
Bt1	56-87 cm; dark reddish brown (5YR 3/3, 3/4) clay; strong very fine angular blocky structure; very hard, firm, very sticky,very plastic; few very fine roots; common very fine and few medium pores; common thin reddish brown (5YR 4/4) clay films on faces of peds and in pores; medium acid (pH 6.0); gradual wavy boundary.
Bt2	87-138 cm; dark brown (7.5 YR 3/3) silty clay with yellowish red (5YR 4/6) coatings; moderate very fine angular blocky structure; firm, very sticky, very plastic; few very fine roots; many very fine pores; common thin reddish brown (5YR 4/4) clay films on faces of peds and in pores; 1 percent of 2 mm size weathered rock fragments in lower part of horizon; very strongly acid (pH 5.0); gradual wavy boundary.
BC	138-185 cm; dark grayish brown (10YR 3/2) silty clay with strong brown (7.5YR 4/6) weathered rock; moderate fine and medium subangular blocky structure; friable, very sticky, very plastic; few very fine roots; many very fine pores; few thin reddish brown (5YR 4/4) clay films on faces of peds and in pores; 5 percent 2-5 mm size weathered rock fragments; very strongly acid (pH 5.0).

2. Haiku clay series (S84HA4-3).

Horizon	Description
Ap1	0-24 cm; brown (7.5YR 4/4) clay; pink (7.5YR) dry; strong very fine and fine subangular blocky structure; very hard, firm, very sticky, very plastic; many very fine and fine roots; many interstitial pores; few fine rounded ironstone concretions, 1 percent pebbles; very strongly acid (pH 5.0); clear smooth boundary.
Ap2	24-47 cm; brown (7.5YR 4/4) and 5 percent reddish brown (5YR 4/4) clay; pink (7.5YR 7/4) dry; moderate very fine and fine and medium subangular blocky structure; firm, very sticky, very plastic; common very fine and fine roots; many very fine pores; pockets of dense clods; few fine rounded ironstone concretions; high bulk density; extremely acid (pH 4.4); clear wavy boundary.
Bw	47-63 cm; yellowish red (5YR 4/6) silty clay; weak fine and medium subangular blocky structure; firm, very sticky, very plastic; common very fine roots; many very fine and few fine pores; very strongly acid (pH 4.5); clear wavy boundary.
Bt	63-75 cm; yellowish red (5YR 4/6) silty clay; moderate very fine and fine subangular blocky structure; friable, very sticky, very plastic, few very fine roots; many very fine pores; common think clay films on faces of peds and in pores; common medium gibbsite nodules; very strongly acid (pH 4.5); clear wavy boundary.
Bt/C	75-88 cm; reddish brown (5YR 4/4) silty clay; moderate fine and medium subangular blocky structure; friable, very sticky, very plastic; few very fine roots; many very fine pores; common moderately thick clay films on faces of peds and in pores; few medium gibbsite nodules; 25 percent dark brown (7.5YR 3/2) soft weathered rock, some of which crushes to silt loam; very strongly acid (pH 5.0); clear wavy boundary (8 to 16 cm thick).
BC	88-130 cm; dark brown (7.5YR 4/4) silty clay with reddish brown (5YR 4/4) coatings; moderate very fine and fine subangular blocky structure and weak fine and medium subangular blocky structure; friable, very sticky, very plastic; few very fine roots; many very fine pores; common moderately thick clay films on faces of peds and in pores; common brownish yellow (10YR 6/6) and pale brown (10YR 6/3) material that formed in seams and appear to be gibbsite; 30 percent weathered rock fragments; very strongly acid (pH 5.0); clear irregular boundary (36 to 47 cm thick).

Horizon	Descriptions
CB	130-196 cm; dark brown (7.5YR 3/4) silty clay; moderate fine and medium subangular blocky structure; friable, sticky, plastic many very fine and few fine pores; few moderately thick clay films; common brownish yellow (10YR 6/6) and pale brown (10 YR 6/3) material that formed in seams and appear to be gibbsite; 75 percent brown (7.5YR 4/2) weathered rock fragments, some of which crushed to silt loam; very strongly acid (pH 5.0).

3. Pauwela clay series (S62HA4-4).

Horizon	Description
Ap1	0-18 cm; dark grayish brown (2.5Y 4/2), grayish brown (2.5Y 5/2) dry; clay; strong fine and very fine subangular and angular blocky with some strong fine and very fine granular structure; hard, slightly firm, sticky and plastic; many roots; common very fine and fine tubular and many interstitial pores; common very fine glistening specks; common fine hard earthy lumps; common wormcast; moderately high bulk density; few fine distinct mottles of 5YR 4/6 due to mixing by tillage; clear wavy boundary.
Ap2	18-30 cm; same color as above; clay; moderate fine and very fine subangular blocky structure; slightly hard, friable, sticky and plastic; many roots; common very fine and fine and few medium and coarse tubular pores; common very fine glistening specks; moderately high bulk density; common wormcasts; occasional areas without structure (massive) apparently due to accumulation of heavy minerals just above the B2 horizon; common medium distinct mottles of 5YR 4/6 due to mixing by tillage; abrupt wavy boundary.
Bt1	30-43 cm; yellowish red (5YR 4/6) clay; yellowish red (5YR 5/6) dry; weak medium and fine subangular blocky structure; soft, friable, sticky and plastic; common roots; many very fine and fine and few medium tubular pores; common patchy glaze on ped faces; few fine hard earthy lumps; normal bulk density; gradual wavy boundary.
Bt2	43-60 cm; same color as above; clay; strong fine and very fine angular blocky structure; slightly hard, slightly firm, sticky and plastic; common roots; many very fine and fine and few medium tubular pores; nearly continuous illuviation cutans; common very fine crumbs of 5YR 4/6 and 7.5YR 4/6 color on some ped faces as observed under hand lens; moderately firm in place; after prolong drying, a redder color of 2.5YR 2/4 is obtained contains occasional sheets varying from 2 to 10 mm in thickness; these sheets are comprised of 5YR 4/6 soil material tending toward a 7.5YR 4/4 color immediately adjacent to the contact; both the top and bottom of these sheets exhibit somewhat of a massive appearance; they have shown a temporary restriction in downward water movement immediately following heavy rains; gradual wavy boundary.

Horizon	Descriptions
Bt3	60-75 cm; dark reddish brown (5YR 3/4) clay; moderate and strong fine and very fine angular blocky structure; slightly hard, slightly firm, sticky and plastic; few roots; common very fine and fine tubular pores; nearly continous illuviation cutans; common fine hard earthy lumps; few fine highly weathered pebbles and rock fragments; after prolong drying, a redder color of 2.5YR 2/4 is obtained; contains occasional sheets as described in above horizon; gradual wavy boundary.
Bt/C	75-103 cm; dark reddish broen (5YR 3/4) clay; moderate and strong fine and very fine angular blocky and subangular blocky structure; slightly hard, friable, sticky and plastic; few roots; common very fine and fine and few medium tubular pores; common highly weathered rock particles, few veins of what appear like gibbsite (1-5 mm thick); gradual wavy boundary.
C	103-138 cm; dark brown to strong brown (7.5YR 4/4 and 5/6) silty clay; weak fine and very fine subangular blocky structure; soft, friable, slightlt sticky, slightlt plastic; no root; many vary fine tubular pores; many highly weathered basic igneous pebbles and cobbles (40-70 percent by volume); few veins of gibbsite oriented horizontally and diagonally.

4. Hamakuapoko series (S84HA4-4).

Horizon	Description
Ap1	0-26 cm; dark brown (7.5YR 3/2) silty clay; brown (7.5YR 5/4) dry; strong fine and very fine subangular blocky structure; very hard, firm, very sticky, very plastic; many very fine and few fine roots; many interstitial pores; few worm holes and casts; 2 percent pebbles; medium acid (pH 6.0); clear wavy boundary.
Ap2	26-50 cm; dark brown (7.5YR 3/2) silty clay; brown (7.5YR 5/4) dry; weak very fine, fine and medium subangular block structure very hard, very sticky, very plastic; many very fine and few fine roots; many very fine pores; 5 percent pebbles; medium acid (pH 6.0); clear wavy boundary.
Bw	50-72 cm; yellowish red (5YR 4/6) silty clay; weak fine and medium subangular blocky structure; friable, very sticky, very plastic; common very fine and few fine roots; many very fine pores; few dark organic stains on some cleavage plane; few worm casts; few think clay films in lower part of horizon; 5 percent pebbles; medium acid (pH 6.0); clear irregular boundary, (10 to 25 cm thick).
Bt/C	72-94 cm; yellowish red (5YR 4/6) and strong brown (7.5YR 4/6) silty clay; strong fine and very fine subangular blocky structure with pockets of weak fine and medium subangular blocky structure; very firm, sticky, plastic; few very fine and fine roots; many very fine pores; gritty due to aggregate stability; common moderately thick clay films and pockets of few thin clay films; 40 percent weathered rock; medium acid (pH 6.0); clear wavy boundary.
Cr	94-141 cm; gray (10YR 6/1) hard weathered rock with yellowish red (5YR 5/6) coatings.

5. Makawao series (S83HA4-12).

Horizon	Description
Ap	0-16 cm; dark reddish brown (5YR 3/3) silty clay; reddish brown (5YR 5/4) dry; strong fine and very fine subangular blocky structure; very hard, firm, very sticky, very plastic; many very fine roots; many very fine pores; very strongly acid (pH 5.0); clear smooth boundary.
Bw	16-30 cm; dark reddish brown (5YR 3/3) silty clay; reddish brown (5YR 5/4) dry; weak find and medium subangular blocky structure; very hard, firm sticky, plastic; many very fine roots, many very fine pores; very strongly acid (pH 5.0); gradual wavy boundary.
Bt1	30-51 cm; dark reddish brown (2.5YR 3/4) silty clay; reddish brown (2.5YR 4/4) dry; moderate very fine and fine subangular blocky structure; very hard, firm, very sticky, very plastic; many very fine roots; many very fine pores; very few thin clay films, firm in place; very strongly acid (pH 5.0); clear wavy boundary.
Bt2	51-97 cm; dark reddish brown (2.5YR 3/4) and dark red (2.5YR 3/6) silty clay; reddish brown (2.5YR 4/4) dry; strong very fine and fine subangular blocky structure; very hard, firm, very sticky, very plastic; few very fine roots and several horizontal seams of root mat; many very fine pores; common moderately thick clay films on faces of peds and in pores; compact in place; very strongly acid (pH 5.0); clear smooth boundary.
C/B	dark reddish brown (2.5YR 3/4) and dark red (2.5YR 3/6) silty clay; red (2.5YR 5/6) dry; strong very fine and fine subangular blocky structure; very hard, firm, sticky, plastic; few very fine roots; many very fine pores; few thin gelatin-like coatings on faces of peds and in pores; 60 percent gravel-size rock fragments; clear smooth boundary.
Cr	123-153 cm; very dark gray (10YR 3/1) hard weathered rock that contains yellowish brown (10YR 5/5) weathered material (iron oxide?); red (2/5YR 4/6) and dark red (2.5YR 3/6) coatings of soil material from above.

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